

TECHNOLOGY APPROACH: DoD VERSUS BOEING (A COMPARATIVE STUDY)

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This is an analysis of different approaches in the use of technology by Boeing and DoD to determine how they may have affected development time for the C-17 and the Boeing 777. Boeing's focus on cost, schedule, performance, and market competition is contrasted to DoD's focus on performance. The paper concludes that the mere existence of a technology should not obscure (a) the impact its maturity may have on program cost and risk, (b) whether it will meet a real need of the user as opposed to a gold plated one, and (c) whether the added development time it may require could pose unanticipated problems for the customer, or even result in fielding an obsolete weapons systems.

The advantage we had in Desert Storm had three major components. We had an advantage in people, an advantage in readiness, and an advantage in technology... We need to preserve that part of the industrial base which will give us a technological advantage... (William Perry, Secretary of Defense) (Mercer and Roop, 1994).

...technology must earn its way on to a Boeing [commercial] plane... In short, our R&D efforts will continue to be customer-driven, not technology-driven (Philip Condit, Boeing president, 1994).

What are the differences in the way private industry and Government approach technology when developing planes? Why does the Government take longer than the private sector to develop a plane?

There's a perception that high technology included in military planes contributes significantly to the typical 11 to 21 years (DiMascio, 1993) it takes the Department of Defense (DoD) to develop, produce, and deploy new military aircraft. To learn if it is the technology that takes so long, this study explores the way Boeing and DoD approached technology in developing the Boeing 777 and the military C-17. One reason for selecting the C-17 is that it does not have the complex weapons systems inher-

ent in fighters or bombers, and yet it still took more than 14 years to develop and deliver. In contrast, it took little more than four years to develop and deliver an operational Boeing 777.

WHAT IS TECHNOLOGY?

According to Webster's Dictionary, technology is defined as "...an applied science that includes the study of industrial arts one can apply toward practical use" (Guralnik, 1980). Technology is a method or process for handling a specific technical problem. By contrast, natural science is: ...the study of knowledge to understand the nature of the subject matter which is being studied. Its purpose is for the sake of understanding—the application or usefulness may not be self evident at that time. Technology is the application of scientific breakthroughs (Goldberg, 1995). When one speaks of a technology breakthrough, one is defining a new process or method for application of a scientific breakthrough.

NEED FOR CHANGE

The Department of Defense is coping with reduced resources and a changing world. At home, the American public continues to demand that its government become more efficient, prompting Vice President Al Gore to initiate a National Performance Review to: "...make the entire federal government both less expensive and

more efficient, and to change the culture of our national bureaucracy away from complacency and entitlement toward initiative and empowerment..." (Gore, 1993).

The late Secretary of Defense Les Aspin directed a "Bottom-Up Review" of DoD to identify cost savings and improve efficiency and effectiveness. In his final report Aspin said: "We must restructure our acquisition system to compensate for the decline in available resources for defense investment and to exploit technological advances in the commercial sector of our economy more effectively..."(Aspin, 1993).

Studies of DoD acquisition over the past 25 years reveal that (a) DoD's way of doing business resulted in programs that spanned 11 to 21 years (DiMascio, 1993), and that (b) by the time the weapon systems were finally delivered the technology was outdated. Significantly, the lengthy time to develop weapon systems was also directly linked to a doubling of the costs originally planned (Gansler, 1989). Based on this past performance one might expect higher costs in the future. Unfortunately, the ongoing process of federal deficit reduction rules out increased military spending. DoD must learn not only to maintain the technological superiority of the American military, but learn to do so in less time and at less cost.

Assumptions

Jacques Gansler warned against DoD's continuing preoccupation with technology without consideration of cost. Substitute schedule for cost, and one could say the same is true for time. As Gansler writes:

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Until the DoD introduces affordability [and schedule] constraints into its requirements process and shifts from a design-to-performance approach to more of a design-to-cost [and design-to-schedule] approach, it will procure fewer and fewer weapon systems each year, and eventually the United States will not have enough modern systems to present a credible defense posture (Gansler, 1989). *[parenthetical material added to original]*

It should not take 21 years to develop and deliver a weapon system nor should advanced technology cost as much as it does. Gansler points out that performance has improved in commercial as well as the defense industry because of technology, "...however, in the defense world costs have risen along with performance." Comparatively, "...commercial computers, televisions, and other items that use similar technology have improved dramatically in performance and gone down dramatically in price," (Gansler, 1989) and don't take as long to produce.

Methodology

This paper is a comparative analysis of the way Boeing and DoD used technology. The problem was to determine whether a difference in DoD's approach to technology contributed to the length of time it took to develop the C-17. This study is based on written works (published and unpublished), interviews, and observances.

Research for this report was primarily focused on the DoD C-17 and the Boeing 777. It included an extensive review of literature and interviews. The literature review encompassed studies, laws, standards, and articles relating to various approaches to technology, their focuses and parameters. The interviews were conducted with individuals who were or had been involved with

the Boeing 777 or the Office of Secretary of Defense (OSD). Additional conversations with senior leaders at Boeing, the Air Force, and DoD revealed their approaches to technology use and their perceptions.

THE BOEING APPROACH

The 777 causes me to sit bolt upright in bed periodically. It's a hell of a gamble. There's a big risk in doing things totally different. (Dean Thornton, President, Boeing Commercial Airplane Group, 1992) (Main, 1992)

Boeing professed a belief that one must approach technology with an eye toward utility...it must earn its way on... (Condit, 1994)

Boeing's conservative approach was illustrated in the 1970s and 1980s when it decided not to include in its 767 more advanced systems such as fly-by-wire, fly-by-light, flat panel video displays, and advanced propulsion systems (Holtby, 1986). Even though the technology existed, Boeing did not believe it was mature enough for the 767. Boeing also used what Gansler defines as a design-to-cost constraint. After Boeing defines a program it evaluates cost before going into production. Its cost evaluations include trade offs of performance, technology, and manufacturing investments (Boeing undated).

In the 1990s Boeing included in its 777 (a) fly-by-wire, (b) advanced liquid-crystal flat-panel displays, (c) the company's own patented two-way digital data bus (ARINC 629), (d) a new wing the company advertised as the most aerodynamically efficient airfoil developed for subsonic commercial aviation, (e) the largest and most powerful engines ever used on a commercial airliner, (f) nine percent composite materials in the

airframe, and (g) an advanced composite empennage (Mulally, 1994). Boeing also invested in new facilities to test the 777 avionics (Proctor, 1994), and to manufacture the composite empennage (Benson, 1995). Did Boeing push the technology envelope for the 777? Philip Condit, Boeing president, said those were technology improvements, not technology breakthroughs. He used fly-by-wire technology to illustrate:

Fly-by-wire is interesting and you can isolate it. But if you step back, our autopilots are fly-by-wire and always have been. We've given it a little bit more authority [in the 777]. The 737 right from the start had what we called a stick steering mode in which you moved the control wheel to make inputs to the auto pilot. Fly-by-wire. The 757 Pratt Whitney engine was completely electronically controlled... it makes neat writing, but it's not an order of magnitude change. Designing the airplane with no mock-up and doing it all on computer was an order of magnitude change (Condit, 1994).

One only has to review the history of airplane technology during the 1980s to see that Condit is right. Airbus and McDonnell Douglas included fly-by-wire on the A340 (Nelson, 1994) and the C-17, respectively, during the 1980s, and both experienced problems. Boeing was able to learn from the mistakes of Airbus and McDonnell Douglas (Woolsey, 1994), and it had the advantage of using new high-powered ultrafast computer chips that increased throughput. In fact Honeywell, the company that McDonnell Douglas dismissed because it couldn't produce the fly-by-wire fast enough

for the C-17, was the company that successfully installed it on the 777 (Woolsey, 1994)—but not without problems.

Boeing could not assemble and integrate the fly-by-wire system until it solved problems with the ARINC 693 databus, the AIMS-driven Flight Management System, and the software coding. Solving these problems took more than a year longer than Boeing anticipated. In order to maintain its schedule, Boeing did as much as it could without the complete system, then it used red-label¹ systems during flight tests. Finally, the Federal Aviation Administration (FAA) certified the last link, the primary flight computer, in March, 1995. In April, 1995 the FAA certified the 777 as safe (Acohido, 1995).

Technical Problems

While Boeing may not define its 777 avionics problems as pushing the technology envelope, Boeing did push the envelope on its design and manufacturing process, and its propulsion. As Condit said, "Designing the airplane with no mock-up and doing it all on computer was an order of magnitude change." When one is the first to use a technology in a new way, one can expect problems. Assuming that Boeing is conservative in its approach, one must ask why Boeing went from computer design to build with no mock-up, and why it used new, large, high-performance engines.

Computer and Aircraft Design

CATIA (Computer assisted three-dimensional interactive application) is the computer application that Boeing used to design the 777 and improve its manufacturing process (Benson, 1994). Jeremy Main best described the reasons Boeing changed

¹ A red-label system signifies that the system is still in the development and testing phase. A black-label system signifies that hardware and software are finished and ready for production.

its way of design and manufacture using CATIA in his article, *Betting on the 21st Century Jet*.

...as a designer, Boeing is preeminent... I have great respect for them, but they have a long way to go in manufacturing. Therefore, to stay on top, Boeing must find ways of building planes better. If Boeing's new approach to design works, the 777 will be an efficient, economic plane with a lot fewer bugs than new planes usually have. As a result, Boeing could save the millions it usually spends fixing design problems during production and after the plane has been delivered to the airlines (Main, 1992).

Boeing's decision to use CATIA in conjunction with a team concept emerged primarily as a means of cutting costs after analysis revealed that the predominant cost drivers were rework on the factory floor and down-stream changes. The teams that Boeing calls design/build teams include representatives from nearly every Boeing function involved in producing the transport, plus customers and suppliers (O'Lone, 1991).

Typically, engineers were still designing when manufacturing began, and they kept making changes as problems subsequently came to light on the factory floor, on the flight line, and even in the customer's hands after the plane was delivered. For example, when Boeing delivered the 747-400 to United in 1990, it had to assign 300 engineers to get rid of bugs that it hadn't spotted earlier (Main, 1992). United was not happy with Boeing's late delivery of the 747, nor with the additional costs the airline sustained in rescheduling flights and compensating unhappy customers as a result of maintenance delays. Boeing was deeply embarrassed by delivery delays and initial

service problems of its 747 (Proctor, 1994). After a lot of research and deliberation, the company decided to use computer aided technology more extensively and change its design and manufacturing approach in order to improve its service. Yet, even though CATIA and the team approach eventually proved worthwhile, there were problems.

Boeing encountered problems in adjusting to 100 percent computer-aided aircraft design. Not only was this a technology change, it was a cultural change. Condit said engineers were reluctant to let others see their drawings before they were 100 percent complete (Condit, 1994). Ronald A. Ostrowski, Director of Engineering for the 777 Division, said one of the initial challenges was to:

...convert people's thinking from 2-D to 3-D. It took more time than we thought it would. I came from a paper world and now, I am managing a digital program (Woolsey, 1994).

The software also had problems and development costs ballooned slightly over budget because of CATIA. Boeing CEO Frank Shrontz said "It was not as user friendly as we originally thought" (Woolsey, 1994).

CATIA and design/build teams were new methods for applying technology that pushed the envelope and could have impacted Boeing's delivery schedule. Instead of allowing a possible schedule slip and late delivery to its United customer, Boeing decided to apply more resources, spend the extra money, overcome its problems, and deliver its 777 on schedule. While Boeing did not state how much it spent, in April 1992 Fortune analysts identified \$3 billion (Main, 1992) set aside for research and development (R&D) for the 777. In April 1994, an editorial in *Aviation Week and Space Technology* estimated that final R&D costs for the 777 approached \$5.5 billion

(AW&ST, 1994). Based on the analysts evaluations one could conclude that actual R&D costs were approximately \$2 billion over planned costs. But, as Alan Mulally, the Senior Vice President for Airplane Development and Definition said:

In our business it's very rare that you can move the end point... When you make a commitment like we made they [United] lay out their plans for a whole fleet of airplanes so it's a big deal. They'll have plans to retire old airplanes. We could have stretched it out but it just seemed best to us to keep the end date the same and add some more resources (Mulally, 1994).

The wisdom of Mulally's decision was proven a thousand times over. The wing assembly tool built by Giddings & Lewis in Janesville, Wisconsin, and the world's largest C-frame riveting system built by Brotje Automation of Germany, were both run in Seattle on programs generated by the CATIA (Benson, 1995). Engineers designed parts and tools digitally on CATIA to verify assembly fit. In Kansas, Boeing's Wichita Division built the lower lob, or belly, of the 777s nose section using CATIA and digital preassembly. In Japan the skins of the airframe were built using CATIA generated programs. Workers at all plants marveled at the way all the parts built by different people all over the world fit together with almost no need for rework (Benson, 1995). Charlie Houser, product line manager at Wichita, said it best:

CATIA and digital preassembly let us find areas of potential interference before we started production. The individual assemblies fit together extremely well, especially the passenger floor. That assembly includes composite floor beams, and

it went together smoother than any floor grid of any size that we've ever built in Wichita (Benson, 1995).

Engines

Three top companies will supply engines for the Boeing 777: Pratt & Whitney, General Electric, and Rolls Royce. The aircraft was designed for two engines that are billed as:

...the largest and most powerful ever built, with the girth of a 737's fuselage and a thrust, or propulsive power, of between 71,000 and 85,000 pounds compared with about 57,000 pounds of the latest 747 engine. Key factors in this performance are new, larger-diameter fans with wide-chord fan blade designs and by-pass ratios ranging from 6-to-1 to as high as 9-to-1. The typical by-pass ratio for today's wide-body jet engines is 5-to-1. Pratt & Whitney is furnishing the PW4000 series of engines, General Electric is offering the GE90 series and Rolls-Royce is offering the Trent 800 series of engines (Donoghue, 1994).

Boeing's success at getting these three companies to produce engines never before produced represent a dramatic change from the time when the federal government was the leader in technology. For example in the 1960s General Electric didn't want to risk the cost and time to develop a high-bypass jet engine for the 747. General Electric was content to let a military development program, the C-5A, absorb the cost and time associated with enhancing high-bypass jet engine technology (Newhouse, 1982). For the 777 Boeing not only pushed for new, more powerful engines, it also pushed for early approval from the Federal Aviation Administration for the plane to fly over oceans (called ETOPS: extended-range

twin-engine operations) (Mintz, 1995).

Normally, the FAA first certifies a twin-engine plane for flights of not more than one hour from an airport, then two hours, and finally, after a couple year's service, a full three hours so the plane could fly anywhere in the world. The 767, powered by Pratt & Whitney JT9D-7R4D/E turbofan engines, became the first Boeing twin to win 120-minute approval in May, 1985, but not until after it had flown for two years (Woolsey, 1991). Jerry Zanatta, Director, 777 Flight Test Engineering, pointed out that engines are so reliable today an airplane could travel on only one engine. Flying with two engines allows redundancy that a pilot wants in order to ensure safety of flight. Flying with more than two engines only increases fuel cost and operating costs unnecessarily. (Zanatta, 1994)

Why did Boeing push propulsion technology? The answer is competition. Boeing's customer airlines are concerned about operating costs and a two-engine plane costs much less to operate than a three- or four-engine plane. Boeing's competition, Airbus, has a twin-engine plane (A330) (Duffy, 1994) that competes favorably with the 777. If Boeing can't deliver, the Airbus can. Still, producing a new engine was not without its problems. For example the Pratt and Whitney engine had performed perfectly in the testing laboratory; but on its first test flight in November, 1993, it backfired several times.

The engine backfired because of differences in the rates of thermal expansion between the interior components of the engine and the compressor case. The case expanded faster than actively cooled interior engine components creating a space between the blades and the case. After the first flight, engineers changed the software commands that direct the variable blade angle of the first four compressor stages to reduce the temperature of the air inside. On the next flight the en-

gine worked perfectly (Kandebo, 1993).

Summary of the Boeing Experience

Boeing looked at its investment in the 777 and its manufacturing process from a tactical and strategic view. It was committed to a successful 777 that would serve its customers and protect its market share against competition for 50 years into the future. Boeing was also committed to changing and improving its manufacturing process using the power of computers so it could improve quality and cut costs well into the 21st century. As a result Boeing management and its Board of Directors were focused on what they had to do to make it all happen. They were willing to commit Boeing resources toward overcoming potential challenges that included computer and process technology.

When Boeing underestimated the challenge of the design-build concept using CATIA, it could have stretched the schedule to spread additional costs over a longer time period. But that would have meant missing the delivery date to United for the first 777. Boeing management made a conscious decision to continue and learn on its first block of 777s so that all future aircraft could benefit.

We could have stretched it out, but it just seemed best to us to keep the end date the same and add some more resources (Mulally 1994).

THE DOD APPROACH TO TECHNOLOGY

Technology on the C-17 was not as well defined as some would have us believe (Brig.Gen. Ron Kadish, 1994).

I was shocked in the Fall of 1992 to discover that this airplane was being produced from paper, that they did not have a CAD/CAM system. That

they had never had a CAD/CAM system (Gen. Ronald Fogleman, 1995).

Secretary of Defense Harold Brown justified using a fixed-price incentive contract to produce the C-17 for two reasons: (a) Congress and President Carter wanted to eliminate cost-plus contracts in order to reduce excessive overruns (Hopkins, 1993), and (b) all the technology for the C-17 was already proven. The Advanced Medium STOL Transport (AMST) prototypes proved short-field take off and landing (STOL) could work and all hardware and software was off-the-shelf (Smith, 1993). The Air Force request for proposal stated that “...Undue complexity or technical risk will be regarded as poor design...” (Johnson, 1986). After McDonnell Douglas won the competition, this theme was carried over into the C-17 technical planning guide:

The C-17's systems are straightforward in design, are highly reliable, and represent current technology. For example, a version of the C-17's engine has been proven in commercial airline service since 1985. New-technology systems, like the onboard inert gas generating system (OBIGGS), are used only where they offer significant advantages over previous methods....Avionics and flight controls that include computer-controlled multifunction displays and head-up displays enable the aircraft to be flown and all its missions accomplished with a flight crew of only two pilots and one loadmaster (McDonnell Douglas, 1993).

However, the C-17 experience revealed what studies conducted during the AMST had proven and Kadish had pointed out—“the technology was not as well defined as some would lead us to believe.” Although

McDonnell Douglas did not develop new technologies for the C-17, the way in which the technologies were used was new. The C-17 was a new cargo airlifter dependent on a complex integrated avionics system to reduce the aircrew size to two pilots and a cargo loadmaster. By comparison the C-141 and the C-5 use two pilots, a navigator for tactical and airdrop missions (C-141 only), two flight engineers, and two cargo loadmasters when carrying passengers (Moen and Lossi, 1995). Also, using STOL capability on a plane expected to fly 2,400 nautical miles (NM) with a 172,200-pound payload to include outsized cargo was much different than using STOL on a plane expected to fly a 400-mile radius with a 27,000-pound payload. The plane would require a new wing and, as John Newhouse points out in his book, *The Sporty Game*, “...there is more technology in the wing than in any other part of an airframe...production schedules are keyed to wings” (Newhouse, 1982). The differences in design between a tactical STOL and a strategic STOL were the catalysts that caused schedule slips and cost money.

Advanced Medium STOL Transport

The AMST was the genesis for the C-17. In 1971 the Air Force contracted both Boeing and McDonnell Douglas to build a prototype that, in the words of Gen. Carlton, was “really a miniature C-5” (Kennedy, undated) to transport cargo in-theater. The plane was to fly a 400 NM radius mission, carry 27,000 pounds, and land on short runways using short landing and take-off (STOL) technology. McDonnell Douglas' YC-15 and Boeing's YC-14 prototypes successfully demonstrated powered lift technology in 1975 that met mission requirements (Kennedy, undated). In March, 1976, the Air Force Chief of Staff Gen. David C. Jones asked Air Force Systems Command to see if it was possible to use a single model of the AMST for both strategic and tactical airlift roles,

and if it was possible to develop non-STOL derivatives of the AMST prototype to meet strategic airlift missions (Jones, 1976). It appears that this strategic study originated with a note from the Chairman of the Joint Chiefs of Staff, Gen. George S. Brown, that asked “Is it practical to have an AMST with a slightly higher box pick up much of the C-5 outsized load for Europe—with air refueling as necessary?” (Lemaster, 1976).

Gordon Taylor and Gordon Quinn from the Aeronautical Systems Division at Wright Patterson Air Force Base, Ohio, were leaders in a conceptual design analysis to determine if DoD could use the AMST for strategic missions. The analysis included reviewing the ability to carry the M-60 Main Battle tank, weighing 110,000 to 117,000 pounds, on a routine basis with ranges from 2,000 NM, 3,000 NM, and 4,000 NM. Taylor and Quinn concluded that using a derivative aircraft in a routine strategic airlift role would increase AMST weight and cost significantly. To restructure the AMST from a tactical to a strategic program would require full-scale development (a larger wing, heavier structure, and different aerodynamics). Even in a non-STOL capacity the wing was the major airframe component that the study said must undergo considerable change (Taylor and Quinn, 1976). In May 1976, Brig.Gen. Philip Larsen, Deputy Chief of Staff, Systems, Air Force Systems Command, wrote:

It would not be cost effective to incorporate a STOL capability in a strategic airlift derivative aircraft. A strategic derivative could employ a less complex conventional flap system which would permit CTOL [conventional takeoff and landing] operations from an 8,000 foot hard surface runway under sea level standard day conditions. The aircraft would be stretched eight feet to provide a 55-

foot-long cargo compartment. This would permit routinely carrying the M-60 tank and single item payloads up to 112,500 pounds, or 14 463L cargo pallets, for distances up to 3,000 NM without refueling. In this particular example, it would be necessary to increase... YC-15 wing area 69 percent and gross weight 115 percent... (Larsen, 1976).

On December 10, 1979, Program Management Directive (PMD) No. R-Q 6131(3) formally cancelled the AMST program. On that same day PMD No. R-C 0020(1) provided formal direction and guidance for activities leading to Full Scale Engineering Development of the C-X. PMD R-C 0020(1) directed that the C-X skip Milestone I and the Demonstration and Validation phase because “...the new aircraft will use existing technology... since the Air Force had demonstrated and proved advanced technology concepts and operational utility in the AMST program” (Johnson, 1986).

Changing Payload Requirements

Payload requirements changed at least five times over the life of the C-17. Beginning in 1981 the request for purchase asked for a STOL plane that could carry a payload of 130,000 pounds (AMC, 1993). McDonnell Douglas claimed it could produce a STOL plane that could carry 172,200 pounds 2400 miles (Johnson, 1986). When the contract was awarded in 1982, the payload requirements were changed to 172,200 pounds (AMC, 1993). DoD did not evaluate the cost to grow from a payload of 130,000 pounds to 172,200 pounds. In 1988 DoD changed the payload requirement from 172,200 pounds to 167,000 in order to accommodate the addition of a 4-pallet ramp and OBIGGS that added 5,000 pounds additional weight to the aircraft (Snider, 1992). In 1991 Gen. Hansford Johnson, MAC Commander, reduced the

payload requirements from 167,000 pounds to 160,000 pounds because the kinds of equipment MAC needed to haul over essential routes—from West Coast bases to Hickam AFB, Hawaii, and from East Coast bases to Lajes airfield in the Azores—did not require a plane with a 167,000-pound capacity. He said:

This was not a reassessment of requirements as much as it was a refinement of the original requirements... McDonnell Douglas, in competing for the contract, offered more than what MAC needed....All of us, being eager to do more, said sure, we'll write the specs at the higher level (Morrocco, 1991).

In January 1995, DoD, Congress, and McDonnell Douglas agreed to decrease the payload requirement even more. If the C-17 were to carry a 160,000-pound payload using short-field take-off and landing capability with the weight of the plane and the required fuel, it needed more powerful engines. Pratt & Whitney and Rolls Royce, had produced more powerful engines, but the Under Secretary of Defense for Acquisition, John M. Deutch, said changing to more powerful engines was too costly. He preferred to reduce payload specifications rather than change engines, especially since the C-17 did not need to carry a greater payload to perform its mission (Morrocco, 1994). Fogleman said that DoD "...allowed the plane to be over spec'd unnecessarily.... We didn't need a plane to carry a 172,200-pound payload then and we don't need a plane to carry 160,000 pounds now" (Fogleman, 1995).

An absolute critical leg for us in this new world we are living in is how much can this airplane carry 3,200 miles...we established a 110,000-pound payload threshold at the

3,200-mile range... The original requirement set in the early 1980s was for a 130,000-pound payload, the weight of an M-1 tank then....this specification is now not considered the most critical. It was linked to the Cold War goal of transporting 10 Army divisions to Europe in 10 days, rather than how to deal with the types of regional contingencies the Pentagon now is focusing on in its planning. An absolute critical leg for us in this new world we are living in is how much can this airplane carry 3,200 miles.... So we established a 110,000-pound payload threshold at the 3,200-mile range which did not exist before...the aircraft meets that goal and is projected to exceed it. Sticking to the original specification would have required switching to more powerful engines (Morrocco, 1994).

On January 17, 1995, the Air Mobility Commander, Gen. Robert Rutherford, declared the C-17 a success when he certified it operationally capable (McDonnell Douglas, 1995). It's worth noting, however, that the program did not begin to overcome technology problems until after top-level commitment was apparent from principals like Deutch (Defense Week, 1995) and Fogleman. Fogleman essentially said this is nonsense, "...we don't need that much payload capability..." (Fogleman, 1995), and Deutch arranged a settlement with McDonnell Douglas that allowed performance trade-offs and help with computer (CAD/CAM) technology. McDonnell Douglas, in turn, put their best people on the job to produce a technically proficient airplane (Morrocco, 1994). As a result of technology trade-offs and top management commitment from both DoD and the contractor, the C-17 exceeded its schedule during 1994 and met mission

requirements in 1995.

Technical Problems

One might say that design problems and planning problems were at the root of technical problems that added time to development of the C-17. The underlying problem was that the players underestimated the technical challenges. Roger A. Panton, Chief of Engineering at the C-17 System Program Office at Wright Patterson AFB, said “Our primary technical problem with the C-17 was integration. We grabbed too much off the shelf and tried to put it together” (Panton, 1994). Critical off-the-shelf technology included fly-by-wire, advanced materials, engines, software, and the powered lift that the McDonnell Douglas YC-15 prototype demonstrated in 1975.

The Defense Science Board added in a December 1993 report that lack of computer aided design and engineering changes contributed to production delays (Defense Science Board, 1993). Deutch summarized some of the most glaring weaknesses as: (a) technical risks involved in flight test software and avionics integration; (b) structural deficiencies in the wings, flaps and slats; and (c) uncertainty of flight test program requirements (Morrocco, 1993).

Avionics Integration

Avionics is a term that covers the myriad of ultrarefined electronic devices on which modern airplanes rely... (Newhouse, 1982).

On the C-17 that includes the flight control system and the mission computer. Integration of the mission computer and electronic flight control system was one of the three critical paths leading to first flight (Smith, 1990). The first test flight of the C-17, September 15, 1991, was behind schedule (Smith, 1991) because of problems that included changing from a standard mechanical flight control system to a quadruple

redundant electronic flight control system, and delays in the mission computer software and flight control software (Hopkins and De Keyrel, 1993).

In 1987, after McDonnell Douglas missed delivery of the first test aircraft, DoD reduced funding during budget reductions and moved delivery schedule for the first test aircraft three years to the right (to July, 1990) (Mastin, 1994). In addition, in January 1988, Congress deducted \$20 million from the C-17 during its budget review, but invited DoD to ask for reprogramming of funds (SAF/AQ, 1989). DoD declined.

Flight Control System

McDonnell Douglas changed to an electronic flight-control system to prevent the plane from entering into a deep stall (Hopkins and De Keyrel, 1993). Wind tunnel testing revealed that the C-17 design caused deep stall characteristics. In 1987 the Sperry Corporation (the flight-control subcontractor) told McDonnell Douglas that the mechanical flight control system could not prevent pilots from putting the airplane into an irreversible stall (ASD/AF/C-17, 1987). After confirming that the aircraft configuration and the mechanical flight control system could allow the aircraft to enter an uncontrollable stall during certain tactical maneuvers, Douglas directed Sperry to change the mechanical flight control to a fly-by-wire system (Smith, 1993). During this same period Honeywell, Incorporated, purchased the Sperry Corporation.

In June 1989, Honeywell officials established April 25, 1991, as the new delivery date for flight qualified software. The additional delay added four years from the time Douglas first asked for the system change until delivery (1987-1991). Even though Honeywell successfully completed an interface control document (ICD) in July 1989, showing how the electronic flight control system (EFCS) interacted with subsystems, the additional delay was too much. Brig.Gen.

Michael Butchko, Air Force C-17 Program Manager, convinced Douglas Aircraft to hire General Electric (GE) for development of a similar system as a precautionary measure (Hopkins and De Keyrel, 1993). Douglas ended Honeywell's contract for the EFCS in July 1989 (Thomas, et al., 1990). GE delivered the version 1 software for integration testing in October, 1990 (Thompson, 1991).

Mission Control Computer

The three mission computers receive data from other systems, analyze data, perform calculations, and display information to the pilot and copilot. The computers act as the heart of the automated avionics system and perform functions normally done by the flight engineer such as determining an estimate of position and velocity, weight limits, airdrop, small airfield approaches, and system management (Thomas, et al., 1990). Each mission computer performs its calculations and then compares its results with the solutions broadcast over the data bus by the other two computers (McDonnell Douglas, 1993).

Douglas awarded a firm-fixed-price contract to Delco in July, 1986, to develop the mission computer (Mundell, 1990). In August 1988, an independent review team that included personnel from McDonnell Douglas, Hughes Electronics, and the Air Force concluded that Delco had not adequately accomplished system engineering and that McDonnell Douglas had not adequately defined the mission computer system requirements. Delco developed the mission computer software enough to hold a critical design review of the detail design in April, 1989 for the first of two increments of software, but it would not commit to a plan for completing the mission computer. In July 1989, Douglas and Delco signed an agreement that partially terminated Delco's contract for the mission computer subsystem, and Douglas assumed responsibility for managing the overall software devel-

opment effort (Thomas, 1990).

McDonnell Douglas subcontracted a majority of software for the C-17 to subcontractors and suppliers. During this process Douglas did not specify a specific computer language, which resulted in software for the C-17 in almost every known language of the time (AW&ST, 1992). Integration of the software was a nightmare that GAO said resulted in "...the most computerized, software-intensive aircraft ever built, relying on 19 different embedded computers incorporating more than 80 microprocessors and about 1.3 million lines of code" (Hopkins and De Keyrel, 1993). The final software release was in September, 1994 with upgrades through March 1995. David J. Lynch, in his article "Airlift's Year of Decision," said that in 1994 the mission computer remained slow and did not meet the desired throughput capacity requirements (Lynch, 1994). John Wilson, C-17 Deputy Program Manager, acknowledged that the program office needs to consider software improvements:

This is a tough area. The C-17 System Program Office recognizes that additional throughput could be beneficial. Although the computer performs the basic mission, it is slow and does not meet the desired throughput capacity. We are working the area (Wilson, 1995).

Wings

The wings, flaps, and slats combine with high thrust engines and the electronic flight control system for short take-off and landing (STOL). Exhaust from the jet engines force air over wings and flaps, generating additional lift. Engines on the C-17 are mounted under the wings and large flaps protrude down into the exhaust stream. The engine exhaust is forced through the flap and down both sides of the flap, creating significant added lift. The externally blown flap system and the full-span leading edge

slats enable the C-17 to operate at low approach speeds for short-field landings and for airdrops (Henderson, 1990). Powered lift enables the C-17 to land on shorter runways than current, large-capacity transports by allowing it to fly slow, steep approaches to highly accurate touchdown points (McDonnell Douglas, 1993). In October 1992, the wing failed a wing-strength test (Morrocco, 1993). Even though Air Force had reduced the maximum payload requirements in December, 1989 from 167,000 pounds to 160,000 pounds at 2,400 NM, the wings were still not strong enough to handle a full payload (GAO, 1994) along with the fuel and structure weight at a 1.5 safety factor. Causes of the failure included a computational error in the initial design, optimistic design assumptions, and the method used to determine compression stress (Huston, et al., 1993). The wing modifications covered a large area because McDonnell Douglas used the erroneous computation throughout the wing structure (Smith, 1993).

The failed strength test was preceded by persistent fuel leaks around the wing in September, 1991, because holes were not drilled and fastened properly. Douglas held up delivery of Production Aircraft for nearly a month while technicians located the leaks. Jim Berry, then Douglas vice-president and general manager of the C-17 program, said the problems stemmed primarily from a lack of production discipline and unscheduled work. The failed wing-strength test and persistent fuel leaks around the wing cost McDonnell Douglas more than \$1 billion, and modifications added an additional 700 pounds in aircraft weight (Smith, 1993).

Summary of the DoD Experience

DoD did not look at its investment in the C-17 from a technically strategic view, nor did it appreciate the challenge of C-17 STOL technology. When DoD changed the mission of the tactical STOL to a strategic

STOL, both McDonnell Douglas and the Department of Defense underestimated the scope and cost of the effort necessary to reduce the aircrew size to three persons and fly 2,400 NM with a 172,200-pound payload. As Fogleman said, DoD "...allowed the plane to be over spec'd unnecessarily....We didn't need a plane to carry a 172,200-pound payload then and we don't need a plane to carry 160,000 pounds now" (Fogleman, 1995). In both cases (reducing aircrew size and requiring STOL) McDonnell Douglas had to increase its use of computerized flight controls in order to maximize performance. In all cases lack of experience with software caused schedule delays and increased cost. In addition a math error caused problems that prevented the C-17 wing from passing the stress test at 150 percent. If McDonnell Douglas had a CAD/CAM system like CATIA, it might have detected and prevented both the stress problems and the fuel leak problems.

CONTRASTING THE DoD AND BOEING APPROACHES

Boeing's focus during the design and acquisition process was on cost, schedule, performance, and market competition. DoD's focus during the design and acquisition process was on performance. Boeing looked at the technology included in its airplane more realistically and did not try to include more than the market would buy. DoD, on the other hand, gold-plated requirements by providing more capacity than the customer needed, and underestimated the STOL technology and cost needed to carry a 172,200-pound payload. Boeing used the CATIA computer program to help revolutionize its design and manufacturing plant so that parts would fit right, and built an entirely new plant to integrate and test its new avionics package. Boeing's investment in infrastructure helped overcome its many

computer and avionics problems. DoD's contractor, McDonnell Douglas, designed the C-17 on paper. McDonnell Douglas did not use a computer program that could have identified and helped eliminate both the wing stress and the fuel leak problems, and it did not adequately plan integration of the C-17 avionics package.

When Boeing underestimated the time and cost to overcome technical problems in the 777 fly-by-wire and CATIA, it determined what it needed to do to correct the problems. Boeing decided to meet its delivery date to United, and commit additional money and resources to solve the technical problems. DoD, on the other hand, upon learning that McDonnell Douglas could not meet its first scheduled flight because of technical problems that included software and STOL design, took money away from the program and stretched it out three years.

Jacques Gansler in his book, *Affording Defense*, explains how DoD's preoccupation with technology is self defeating:

...the unreasonably long acquisition cycle (10-15 years)...leads to unnecessary development costs, to increased "gold plating," and to the fielding of obsolete technology (Gansler, 1989).

What happens is that DoD takes so long to overcome technology problems that by the time a weapon is complete, the technology is outdated. In the case of the C-17, that's true. It is the most versatile up-to-date cargo plane the U.S. currently has, but DoD couldn't produce the C-17 until the technology problems of design, fly-by-wire, embedded computer systems, and wing stress were solved. As a result, Boeing completed the 777 at about the same time even though it was conceived several years after the C-17. The 777 uses the same level of

technology or, as with flat-panel displays, computer-design, increased propulsion, and manufacturing processes, it uses more advanced technology.

Jacques Gansler describes the dilemma between the Defense and commercial approach to technology in his illustration of a college student working in the commercial world versus one who works for defense.

A typical American engineering student (graduate or undergraduate) is taught how to design the "best system." Using computers, sophisticated mathematics, and all their engineering skills, these students set out to design systems that will achieve the maximum performance. If they enter the commercial world, they are taught that their designs should be modified to reduce the likely costs of production and operation. However, if they enter the defense world, they continue to use the design practices they learned in school, and cost-cutting becomes an exercise for the manufacturer (Gansler, 1989).

If DoD continues its past preoccupation with technology, it will fall behind. In the past commercial development programs leveraged the technology developed by the military; this was certainly true for the 777 fly-by-wire. However, the military is now learning from commercial developers. The F-22 and other acquisition programs are using the integrated product teams that Boeing developed in its design-build approach. The F-22, the B-2, and the V-22 Osprey are all benefitting from CATIA and the strides Boeing made in composite manufacturing. However, the programs are not benefitting from Boeing's design-to-cost approach.

CONCLUSIONS

Did the difference in approaches to technology contribute to the length of time it took to develop the DoD C-17 compared to the Boeing 777? One would have to say yes. The most telling difference was how Boeing and DoD reacted to technical problems that threatened to impact delivery dates. Boeing added more resources to overcome technical problems whereas DoD

took resources away and moved the delivery date out three years. As long as DoD overestimates the maturity of technology it wants to use, asks for more technology than it needs, does not commit resources to overcome technology problems in a timely manner, and does not require cost, schedule, and technology trade-offs during evolution of the design, it will take longer to develop weapon systems.

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